ABRASION WEAR OF SOME WROUGHT HEAT TREATED STEELS DURING JAW CRUSHING OF AN INDIAN IRO NORE

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JULY, 1980

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A Thesis Submitted
in Partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

BY

EDWIN SAMUEL

to the
DEPARTMENT OF METALLURGICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR

JULY, 1980

CERTIFICATE

This is to certify that this work on 'Abrasion wear of some wrought Heat Treated Steels during Jaw Crushing of an Indian Iron Ore' has been carried out under my supervision and it has not been submitted elsewhere for a degree.

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ACKNOWLEDGEMENT

I sincerely thank Dr. G.S. Upadhyaya for his valuable guidance throughout this present investigation.

I gratefully acknowledge Dr. T. Mukherjee, Divisional Manager Scientific Services, TISCO, Jamshedpur who suggested us this topic and for all the assistance he provided. I sincerely thank the General Manager (Oprn.), The Tata Iron and Steel Co. Ltd., Jamshedpur for the materials that were provided and for permission to conduct the tests at TISCO.

Our grateful thanks are due to Dr. V.A. Alteker, Director, National Metallurgical Laboratory, Jamshedpur for kindly extending us the facilities for scanning electron metallography.

Lastly I thank all who have assisted me in completing the thesis.

EDWIN SAMUEL

ABSTRACT

In the present investigation the abrasion wear of some wrought heat treated steels - IS 226, LA 60 and TISCRAL grades, have been studied. The wear tests were carried out using a laboratory size jaw crusher with iron ore. The wear of the steels were measured relative to Hadfield manganese steel and reported as wear ratio. The wear resistance of various steels have been interpreted in terms of hardness and microstructural characteristics.

CONTENTS

CHAPTER I

LITERATURE REVIEW

I.1 Introduction

Abrasive wear occurs as a result of dynamic contact between metallic wearing surfaces and abrasive particles or fragments. Abrasive wear occurs in a wide variety of operations including mining, earth moving, mineral beneficiation chemical processing, agriculture, foundry and ceramics manufacture. Abrasive wear may be a 2-body abrasion or 3-body abrasion.

In 2-body abrasion, the abraded particles are transported across the wearing surface with little communition, e.g. ore handling machinery. In 3-body abrasion high stresses are present resulting in particle size reduction e.g. ore crushing equipments.

Abrasive wear is a severe type of wear encountered particularly in mineral processing industry.

I.2 Types of Abrasive Wear

Although the conditions under which abrasive wear occurs vary widely with each application, these conditions may be classified into 3 distinctive types as follows:

1. Gouging abrasion, usually with impact.
2. High stress or grinding abrasion.
3. Low-stress scratching abrasion or erosion.

Sometimes, more than one of these types of wear occurs simultaneously on a wearing part, but usually the predominant type can be recognised.

I.2.1 Gouging Abrasion

This type of abrasion implies a condition where rocks or other types of coarse abrasive materials cut into a wearing surface with considerable force to tear off relatively large particles of metal from the wearing surface. Sometimes such gouging forces are applied at relatively low velocity, as in the case of a shovel dipper into a rock pile, in other cases, they may be applied at high velocity, as in the case of the hammers or breaker bars in an impact type pulverizer. The mechanism of metal removal is similar to that produced by machining with a cutting tool or abrasive wheel.

I.2.2 Grinding Abrasion

High stress or grinding abrasion occurs when two wearing surfaces rub together in a gritty environment with sufficient force to produce a crushing action in the mineral particles or other abrasive entrapped between these two

surfaces. Quartz and silicate minerals often produce such wear resulting from abrasive forces. Although the nominal load per unit of surface area may appear to be low, the actual stress which acts on microscopic areas, as a result of indentation or scratching by the abrasive is quite high. Some comprehension of the unit stresses involved can be obtained from the fact that quartz grains are capable of indenting or scratching the hardest types of steels. Therefore, the unit stresses are capable of causing micro-spalling or fracturing of brittle constituents (such as coarse carbides) which may exist in the structure of some wear resistance alloys.

Ball mill grinding provides one of the principal applications where high stress abrasion occurs. Other industrial applications exist where dirt and grit are unavoidably trapped between two bearing surfaces, such as in conveyor chains and sprockets, open gears, and exposed parts of earth moving equipments.

I.2.3 Low Stress Scratching Abrasion or Erosion

This involves surface contact, with some degree of velocity, between relatively freely moving abrasive particles and a wearing surface. The forces are seldom high enough to cause much crushing or breaking of the abrasive grains. The

grains are most frequently suspended and carried in a fluid such as air or water. In some cases when the grains are subjected to motion and they produce wear by their own weight as for example sand sliding down a chute. In most instances of erosive wear, the abrasive particles are small so that impact forces on the wearing part are usually negligible(1).

I.3 Factors Affecting Abrasive Wear

The basic mechanism of abrasive wear has been the subject of many investigations. Two processes can be identified as taking place when abrasive grains make contact with the wearing surface:

1. The formation of plastically impressed grooves which does not involve metal removal and
2. The separation of metal particles in the form of microchips(2).

Other investigations show that some of the contacting abrasive grains are purely elastic on the wearing surface and that the extruded fins at the edges of grooves produced by rubbing can sometimes become detached forming secondary chips, although it is the primary chips which predominate in terms of metal loss(3). A comprehensive study reveals that the number of contact points per unit area of wearing surface

varies with the size of the abrasive particle and the proportion of contacts producing a chip is approximately constant and as low as 12 pct.[4] More recently this figure has been reported as 50-60 pct.[5] Apart from the proportion of contacts the abrasive must make a contact at an angle greater than the 'critical attack angle' with the wearing surface[4].

I.3.1 The Effect of Properties of the Abrasive

Abrasive type and relative hardness.

Several investigations have shown that relative wear resistance is not independent of the hardness of the abrasive[6-9]. When the hardness of abrasive is very much greater than the hardness of the wearing surface,the wear is independent of abrasive hardness. As the hardness of the wearing surface approaches that of the abrasive, wear decreases rapidly.

The different strength properties of abrasives and their mode of deterioration may account for the importance of their relative hardness[10]. Attrition caused by chemical degradation of the surface and fragmentation due to relief of internal stresses are two abrasive deterioration mechanisms. It is found that oxide structures

wear more by fragmentation and carbides and borides wear more by attrition[11].

Abrasive Grit Size

It has been established that volumetric wear increases steeply with grit size to a critical size and and then increases at a reduced rate with further increasing grit size, (Fig. 1.1)[12]. From the graph it is apparent the gradient of both linear portions of the wear/grit size curves increases with decreasing wear resistance,and also the critical grit size.

Abrasive Shape

Chips formed during abrasion are cut depending upon the shape of the abrasive particle[3]. It was found that soft angular particles produced more wear than rounded hard particles[13]. In a study of abrasion by loose graphite and molybdenum disulphide particles, the abrasion rate increases as the particles becomes less plate like. It was suggested that this is because plates are more likely to be flat at the interface[14].

I.3.2 The Effect of Variables Other than the Abrasive

Speed

The volumetric wear increases with speed and is more marked for larger abrasive particle size. This is suggested due to frictional heating[12].

Load

Several investigations[12] have shown that volumetric wear is directly proportional to the nominal load upto a critical load which is determined by the onset of massive deformation of the wearing surface. A deviation from this linearity is reported at lower loads for the smaller grit sizes[12]. It has been suggested that failure of the abrasive commenses when the applied load on an abrasive particle reaches a value corresponding to a groove width of about 0.17 of the abrasive particle diameter, since groove widths are fairly constant with load while the number of contact points increases roughly linearly with load. Further the wear load relationship is such that the wear/unit load decreases as the load increases and the sensitivity of relative wear to increase with decreasing contact, stress varies for different materials[5,9].

Frictional Heating

Frictional heating due to abrasive wear though negligible at low speeds, is the cause for increase in wear rate at high speeds[12]. Temperature rise of 325-900°C in the grit chip contact zone have been reported leading to modification of physical, chemical and mechanical properties of the contact zone although the overall effect on the abrasive wear was small[15]. In grinding operations where relative speeds are much higher temperature rises as high as 1500°C[16].

I.4 Abrasive Wear in Relation to Mechanical Properties

I.4.1 Elastic Modulus and Elastic Limit of Strain

It is possible to assign wear resistance to a material by the amount of elastic deformation a wearing surface can sustain to accomodate the abrasive grit with no plastic deformation or removal. It has been suggested that at equilibrium an abrasive particle dislodges metal ahead of it plastically but that material behind recovers elastically so that the volume wear depends on the elastic recovery of the surface and is inversely proportional to the elastic modulus[17]. It has been found that wear resistance for pure metals can be related to the modulus of elasticity,(Fig. 1.2).

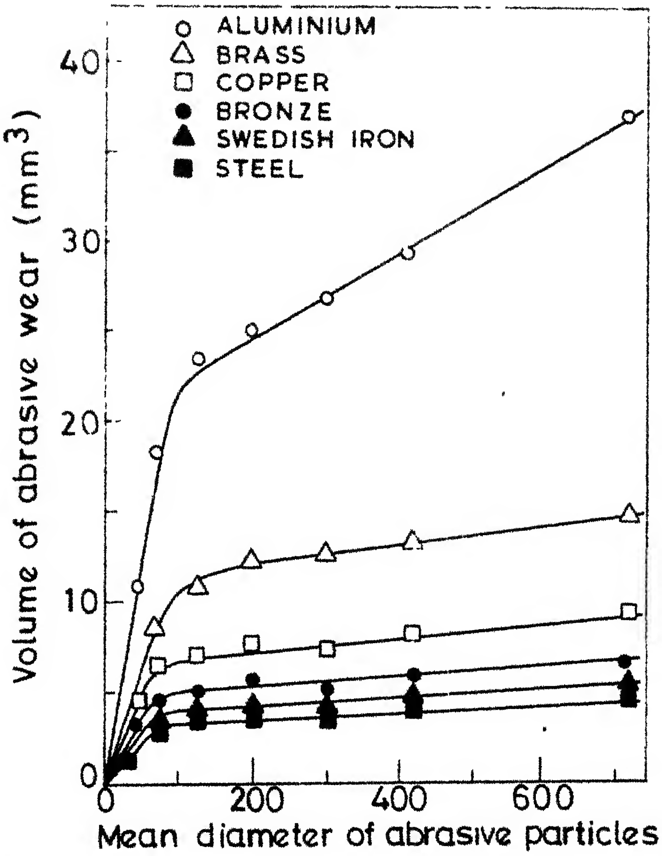


Fig.1.1 The effect of abrasive grit size on volume wear [12].

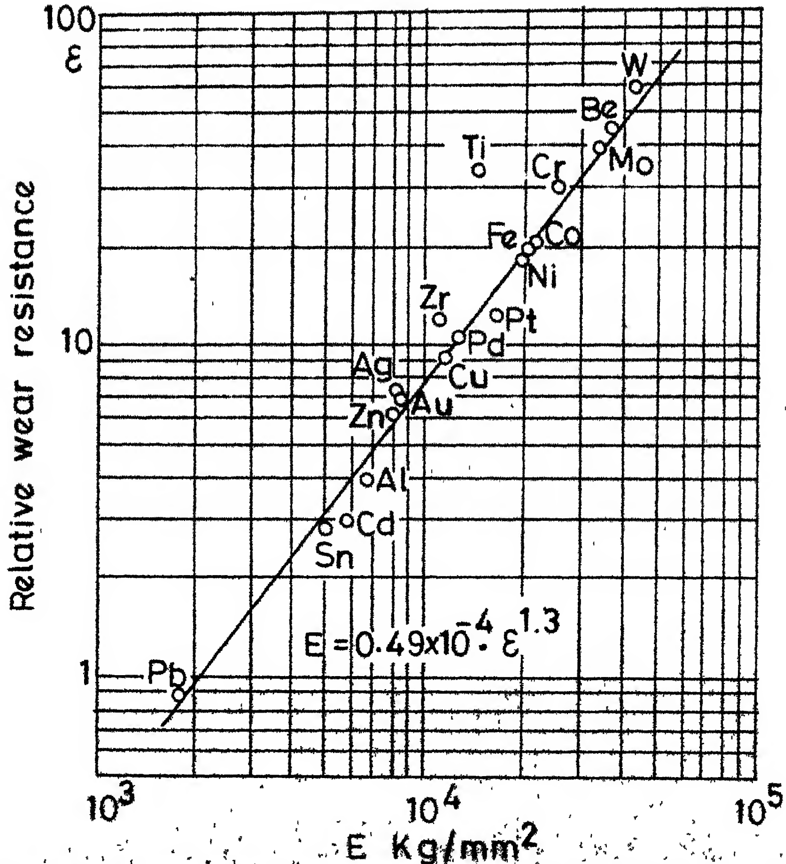


Fig.1.2 The dependence of wear resistance of some pure metals on modulus of elasticity [18].

But this relationship does not hold good for heat treated steels[18].

I.4.2 Bulk Hardness

The relationship between wear resistance and bulk hardness is often used to present abrasive wear data. (Fig. 1.3). It has been shown that the wear resistance of pure metals is directly proportional to their hardness[19]. It has also been found that linear relationship exists between wear resistance and hardness for heat treated steels and some metal carbides. For steels the data fitted an equation of the type

$$\beta = \beta_o + C (H_v + H_{v_o})$$

where β is the relative wear resistance of the steel. β_o is the relative wear resistance in the annealed condition 'C' is a constant, H_v is the Vickers diamond pyramid bulk hardness of the steel, and H_{v_o} is the hardness of the steel in the annealed condition. The constant 'C' varies systematically with carbon and alloy content of the steel. It has also been shown that impurities and alloying elements in the pure metals do not produce increases in wear resistance proportionate to increases in hardness[8].

I.4.3 Surface Hardness

In the absence of a single relationship between bulk hardness and wear resistance it has been concluded that a high degree of strain hardening occurs at the surface of worn metals, and that wear resistance depends on the strength of the material in its 'maximum work hardened state'[2].

It is argued that the abrasion process is to a considerable extent dependent upon the indentation of the abrasive grains into the metal surface and that a relationship existed between the surface hardness after wear and wear resistance[20]. For a group of materials for which the rate of strain hardening is a function of the bulk hardness, the hardness of the abraded surface will be a function of the bulk hardness, and so abrasive wear resistance may be proportional to both these properties[21,22].

It has been found that for materials strained by shot peening, trepanning, the whole of the effective surface does not strain harden to the same level, athough limited regions reach a 'maximum hardness', H_V. Abrasion resistance correlated with this maximum hardness shows a direct proportionality in limited cases of materials[23]. Recent analyses have shown that the limiting strength

attained at worn surfaces can be understood in terms of metallurgical structure and suggest that the limiting strength is a measure of the maximum dislocation density that can be stored by the material.

I.4.4 Flow and Fracture Properties

In a theoretical analysis of the stress strain system developed in the wear process, a power law has been used to describe the stress strain curve of pure metals

$$\sigma = A\,\varepsilon^n$$

where σ is the flow stress, A is a constant, ε is true strain and n is the strain hardening exponent. The abrasion resistance is found to be proportional to either bulk or surface hardness and exponent (n). Therefore abrasion resistance plotted against surface or bulk hardness should give a straight line through the origin with some scatter due to the spread in values of the strain hardening exponent n[21,22]. For instance the different wear properties of hexagonal and cubic metals has been attributed to the difference in their slip processes which cause their strain hardening[24].

For interstitial and substitutional solid solutions, precipitation and dispersion hardened materials a single

relationship between wear resistance and bulk or surface hardness does not exist because of the wide variation in their strain hardening exponents. Various models for dispersion hardening have been considered and found that finely dispersed hard particles influence the flow stress and increase abrasion resistance according to a Hall petch (i.e. Abrasion resistance is inversely proportional to the square root of cementite particle spacing) (Fig. 1.4)[21] relationshi An investigation of sintered aluminium type alloy found that abrasion resistance is directly related to the fineness of the dislocation substructure formed in the abraded surface and inversely proportional to the square root of the particle spacing and that the flow stress responsible for abrasion resistance is governed by the Ansell Level mechanism (i.e. flow occurs when the shear stress on particles due to dislocation pile-ups deforms or fractures the particles)[25]. Using a model relating flow stress to the precipitate spacing and size, the wear ratio has been related to structural changes occuring during age hardening and found that the wear is practically independent of the ratio particle spacing/particle diameter[26].

I.5 Abrasion Resistance of Wrought Steels

I.5.1 Plain Carbon Steels

The low carbon unalloyed mild steels are used in abrasion situations because of their ready availability low cost and good toughness and ease of fabrication. In applications where wear occurs slowly so that frequent replacement is not a problem this material is an economical choice. Basic microstructure is a decisive factor determining abrasion resistance. For example wear resistance is a function of cementite content(Fig. 1.5)[27]. Also it has been reported that lamellar pearlitic structure has better wear resistance than a spheroidised structure. The wear resistance increases as the interlamellar spacing decreases. In hypereutectoid steels wear resistance continues to increase with carbon content and drops when cementite begins to appear as grain boundary network.[28]

I.5.2 Alloy Steels

In case of alloy steels, various heat treatments, which alter the alloy matrix and dispersion of carbides, have a decisive influence on their capacity to resist abrasive wear. A study of effect of different methods of hardening steel on abrasive wear resistance has shown that

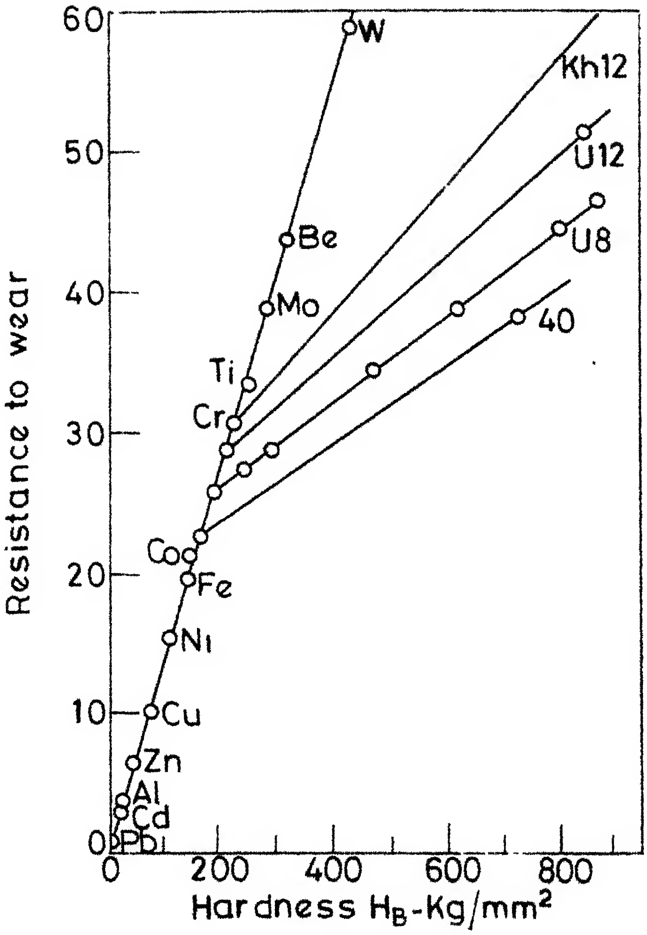


Fig.1.3 The dependence of relative wear resistance of some pure metals on bulk hardness [19].

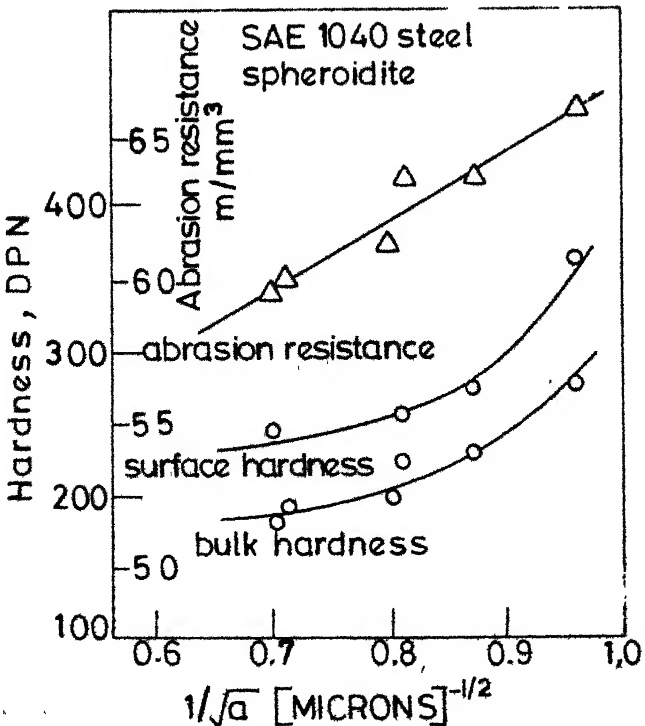


Fig.1.4 The dependence of wear resistance of spheroidal cementite on the particle spacing [21].

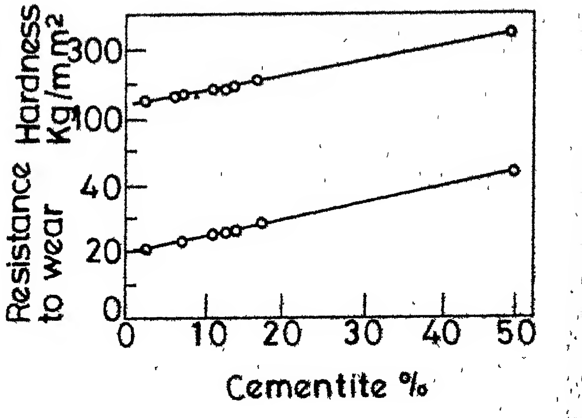


Fig.1.5 The dependence of wear an hardness on cementite % of irons and steels [27].

improvement of wear resistance is maximum due to alloy additions. Then comes quenching and tempering heat treatments followed by strain hardening,(Fig. 1.6)[29].

Direct evidence of the effect of the carbide phase on the abrasion resistance of several 6 Mn - 5Cr - 1Mo steel has shown to be directly a function of volume fraction of carbides precipitated in the matrix (Fig. 1.7)[30].

A study of abrasion resistance of wrought alloy steels, (Fig. 1.8)[31],Table 1.1 has shown that the carbon content and microstructure play a vital role.

The effect of microstructure of various steels result in a band spread in the wear ratio versus carbon content plot. For the same carbon content and other alloying elements a range of wear properties is obtained. There is a tendency for ferritic and austenitic materials to be nearer the upper boundary of the band, while alloys with martensitic structures tend to be closer to the lower boundary[31].

The abrasion resistance of various alloy steels has been reported to correlate well with hardness of work hardened surface (Fig. 1.9). The correlation shows that the higher work hardened values favour increased gouging wear resistance[31].

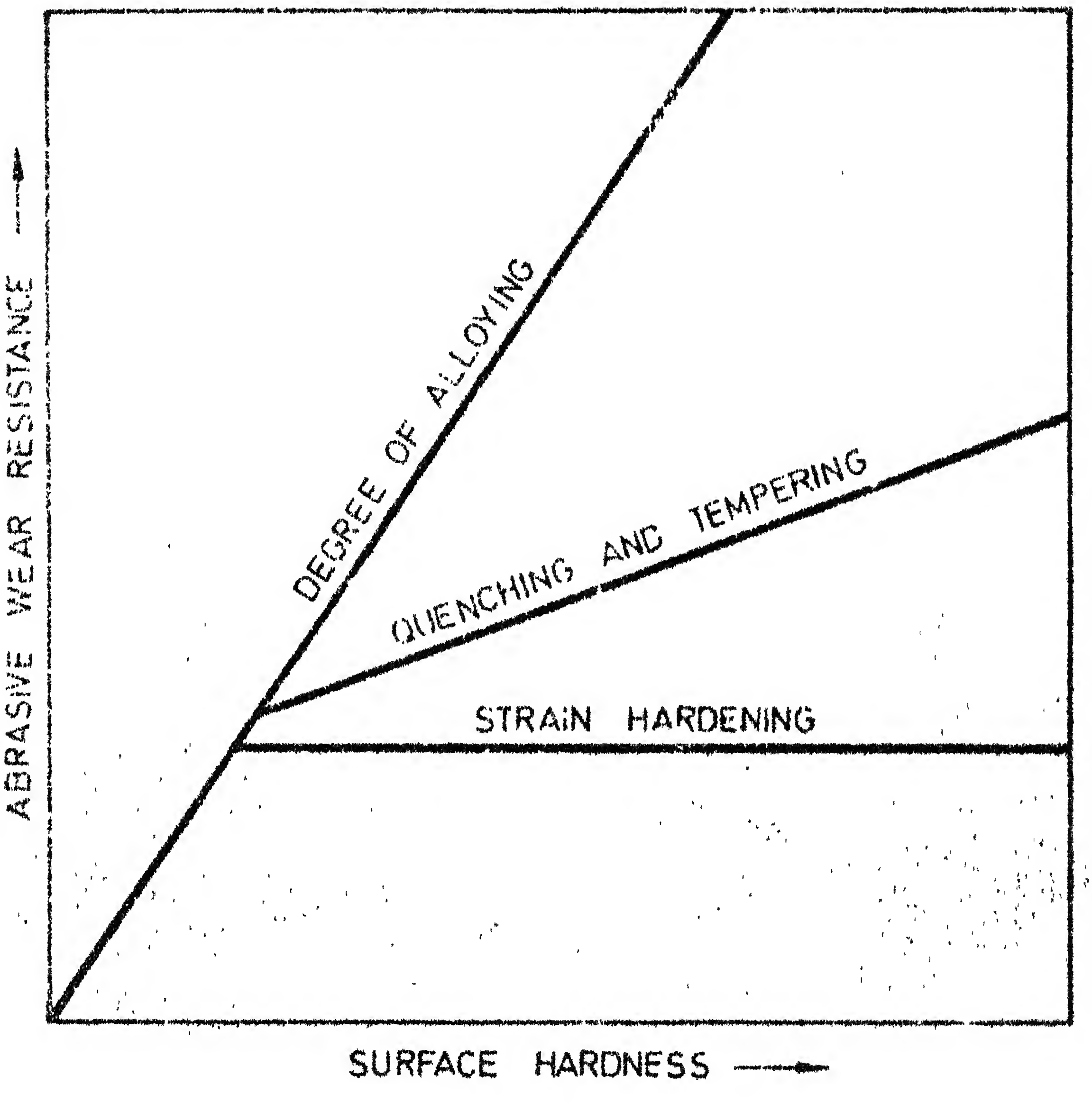


FIG. 1.6 Different Methods of Improving Abrasive Wear Resistance in Steels. [29]

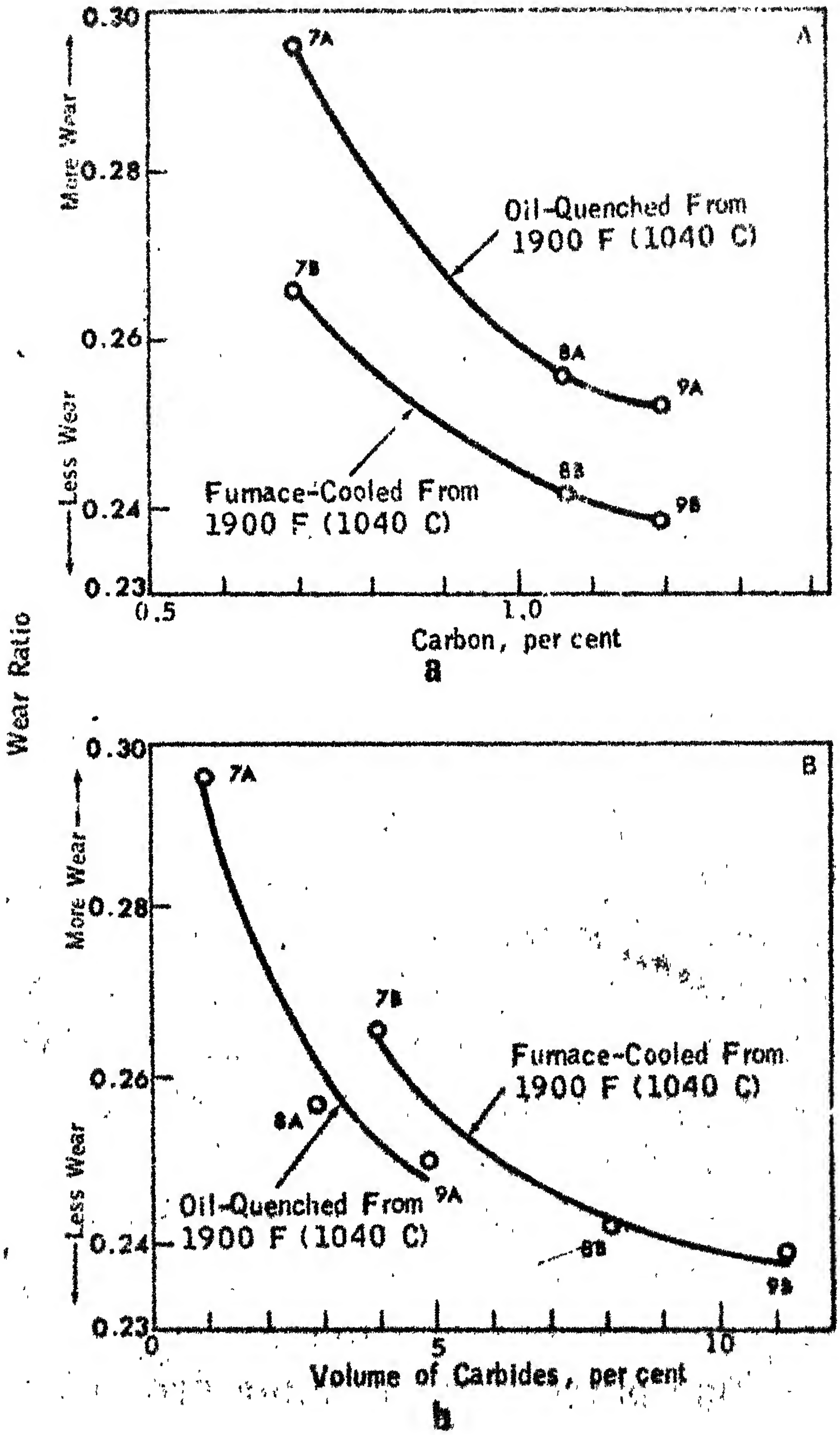


FIG. 1.7 Relationship between (a) Carbon Content and Wear Ratio (b) Amount of Carbides and Wear Ratio of Several 6Mn-5Cr-1Mo Steels.[30].

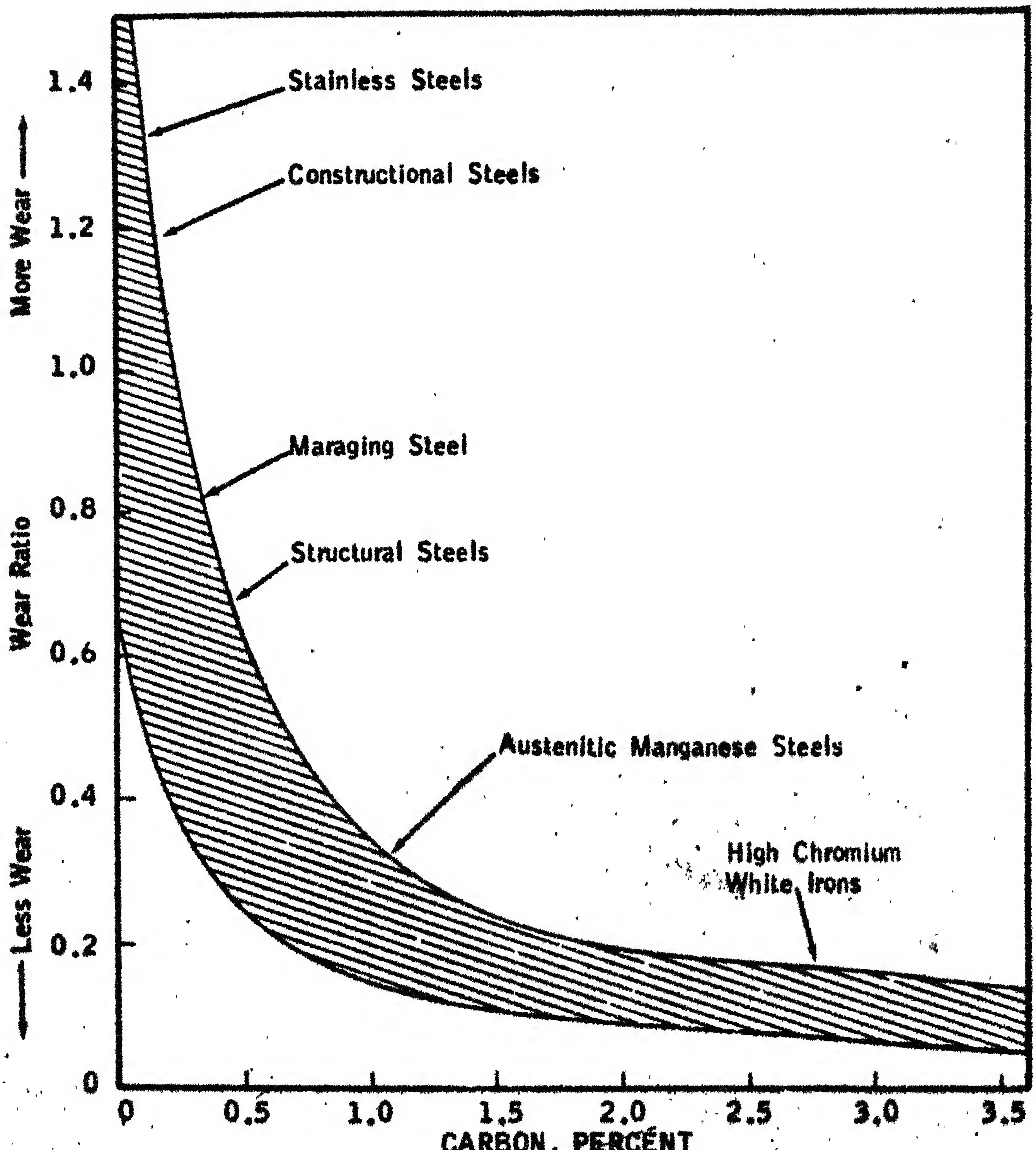


Fig. 1.8—Relationship between the gouging wear ratio and the carbon content of various classes of ferrous materials. [31]

TABLE 1.1 Wear Resistance of Some Wrought Steels

Material	Composition	Heat Treatment	Microstructure	Wear ratio
1. Low alloy steel	.19C, .84Mn, .28Si .56Cr, .18Mo, .011P, .021S, .02Ti, .05V, .0032B	Water quenched from 927°C, tempered at 650°C	Ferrite, carbide	1.084
2. SAE 4340	.4C, .7Mn, .3Si, .8Cr, 1.8 Ni, .25 Mo	1. Austenized (955°C–2hrs) air cooled	1. Ferrite, pearlite	0.674
		2. 870°C 2 hrs, oil quenched tempered 650°C	2. Ferrite, carbide	0.716
		3. 870°C 2 hrs, oil quenched tempered 205°C	3. Tempered martensite	0.232
3. 8Cr–18Ni–5Mo Maraging Steel	.01C, .08Mn, .06Si 8.98Cr, 18.25Ni, 4.96Mo, .005P, .004S, .7Ti, .02 Zr, .003B	815°C–1hr 480°C–3hrs air cooled	Martensite with 10 pct. retained austenite	0.705
4. Type 304 Stainless Steel	.08C max, 2.0Mn, 1.00Si, 18–20Cr, 8–12Ni, .045P, .03S	As received (Annealed)	Austenitic	1.192
5. Type 316 Stainless Steel	.042C, 1.6Mn, .51Si, 17.17Cr, 13.5Ni, 2.23Mo, .017P, .024S, .29Cd, .24Cu	Annealed 1040°C–1hr water quenched	Austenitic	1.291

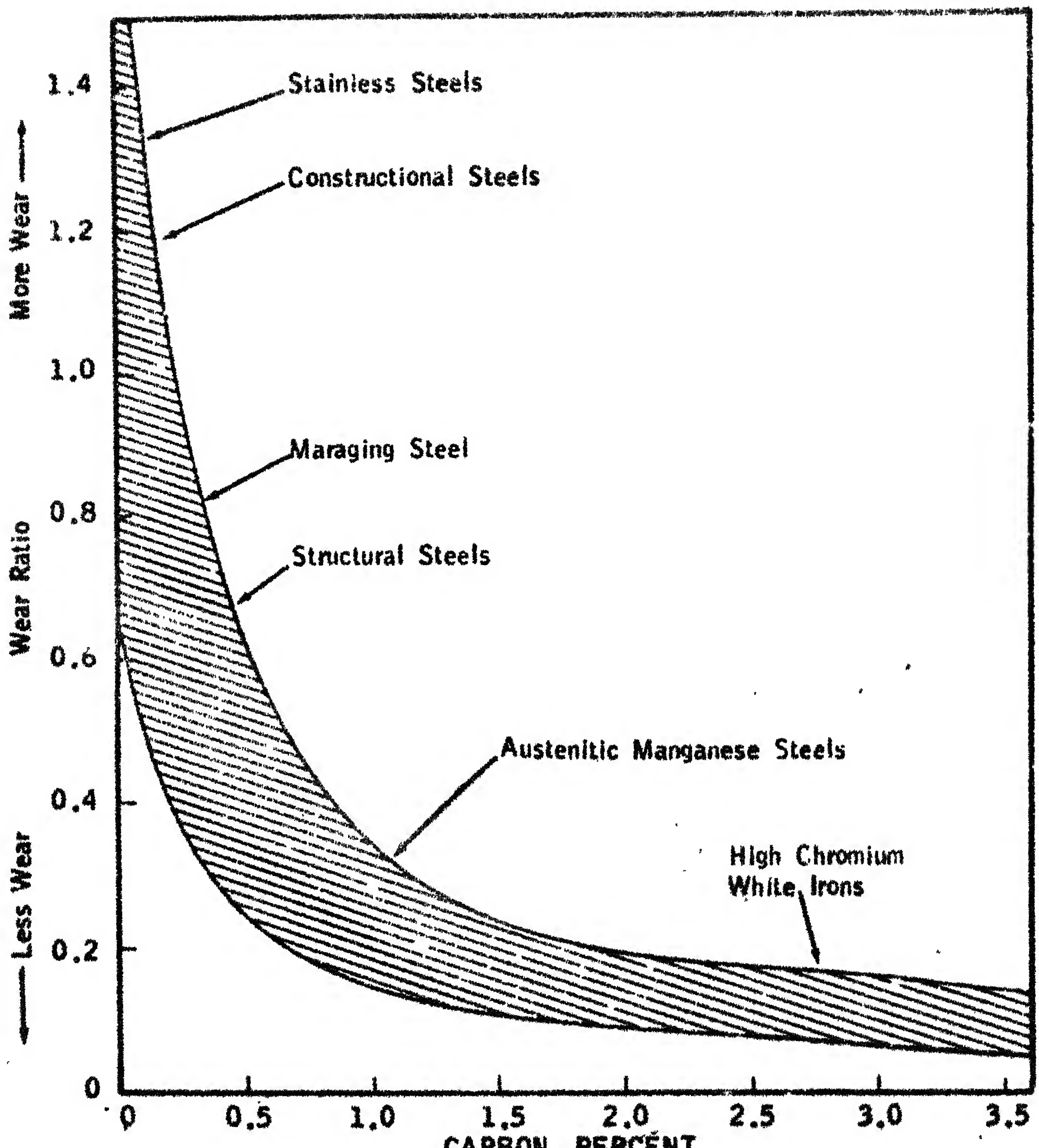


Fig. 1.9—Relationship between the gouging wear ratio and the carbon content of various classes of ferrous materials.

The best wear resistance has been obtained in an alloy steel with a structure of uniformly distributed fine carbides in a martensitic matrix with some residual austenite[28]. It is essential however, that the appearance of residual austenite in the matrix is not accompanied by a decrease in carbide content. Residual austenite is thought to add toughness to the matrix, provide support for the alloy carbides and be capable of undergoing transformation to martensite locally during abrasive wear[28].

Martensite is reported[29] as an important microstructural component that enables steel to resist gouging wear to a greater degree than does ferrite or austenite. This is clearly demonstrated by quenched and tempered SAE 4340 grade which has a wear ratio comparable to austenitic manganese type steel[29].

I.6 Scope of the Present Work

Abrasive wear is one of the most expensive types of wear occuring in mining and ore processing industries. The literature survey made presently reveals that several attempts have been made during the last 50 years to simulate abrasive wear or a laboratory scale and to study the wear resistance of different materials. Hall[33] was the first to study gouging wear by measuring the weight loss of the wear plates of a small jaw crusher. This wear test closely simulates the gouging wear processes operating in actual systems.

Many factors, including physical and metallurgical, control abrasive wear. For the same chemical specification of a steel, a range of wear properties could be obtained[30]. This is attributed to the different microstructures obtained by various heat treatments.

3 grades of steel namely IS226, LA 60, and Tiscral (detailed specification given in Chapter II) made by Tata Iron and Steel Company, Jamshedpur were selected for the present wear studies. IS 226 being a plain carbon mild steel, while LA 60 and Tiscral were low alloy steels. LA 60 steel was a high strength low alloy steel exhibiting grain refinement and precipitation hardening response. Tiscral was a ferrito-pearlitic weldable quality steel being marketed as wear resistant steel by TISCO, which is relatively cheaper compared to LA 60 steel.

CHAPTER II

EXPERIMENTAL PROCEDURE

II.1 Details of Jaw Crusher and Materials

A laboratory-scale jaw crusher of capacity 2 tons/hr very similar to the one used by Borik and Sponseller[32] was used to determine the abrasion resistance of the jaw plates. (Fig. 2.1).

The crusher used was an overhead eccentric, single toggle type jaw crusher. The essential parts are illustrated in Fig. 2.2 and identified by numbers 1 through 12[32].

While the fixed plate (1) is held against the frame by two check plates (3) as shown in the figure, the pitman[5] and the movable plate have a complicated movement. At the top of the crushing chamber the motion of the plate is a wide ellipse, while near the discharge opening the motion is a narrow ellipse. The crushing action at all points in the crushing chamber has both vertical (shearing) and horizontal (compression) components.

As different from the jaw crusher used by Borik and Sponseller where the discharge opening could be adjusted by a wedge (10), in the present set up the gap was adjusted by introducing cut steel sheets behind the fixed and

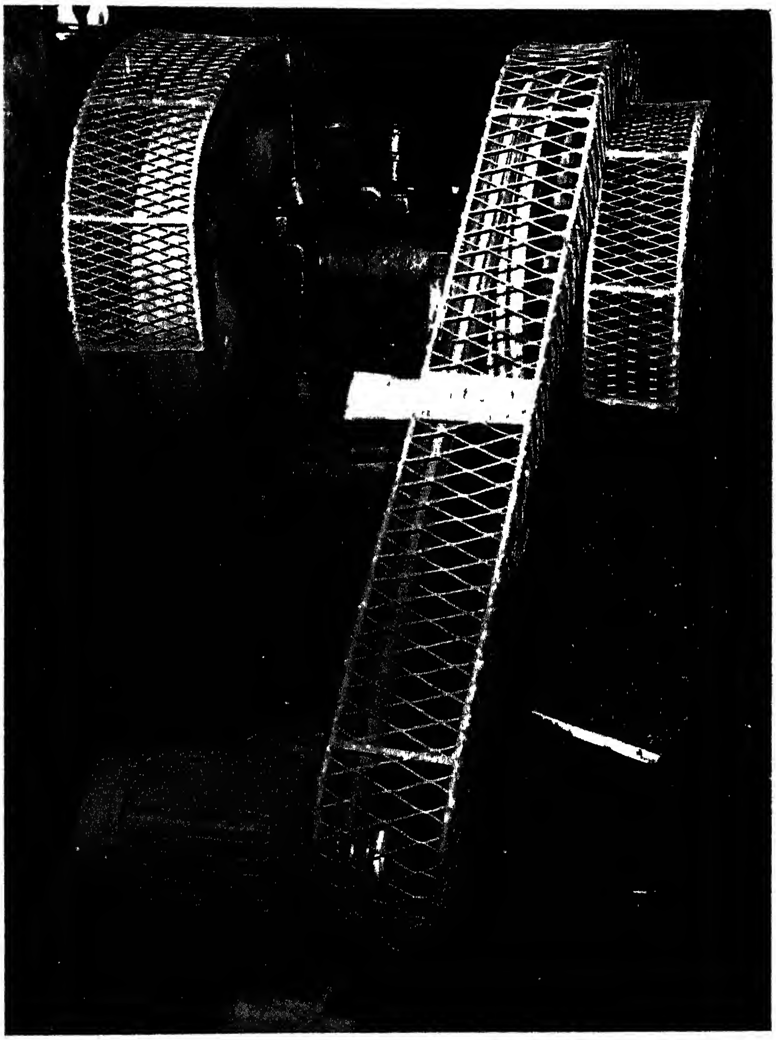
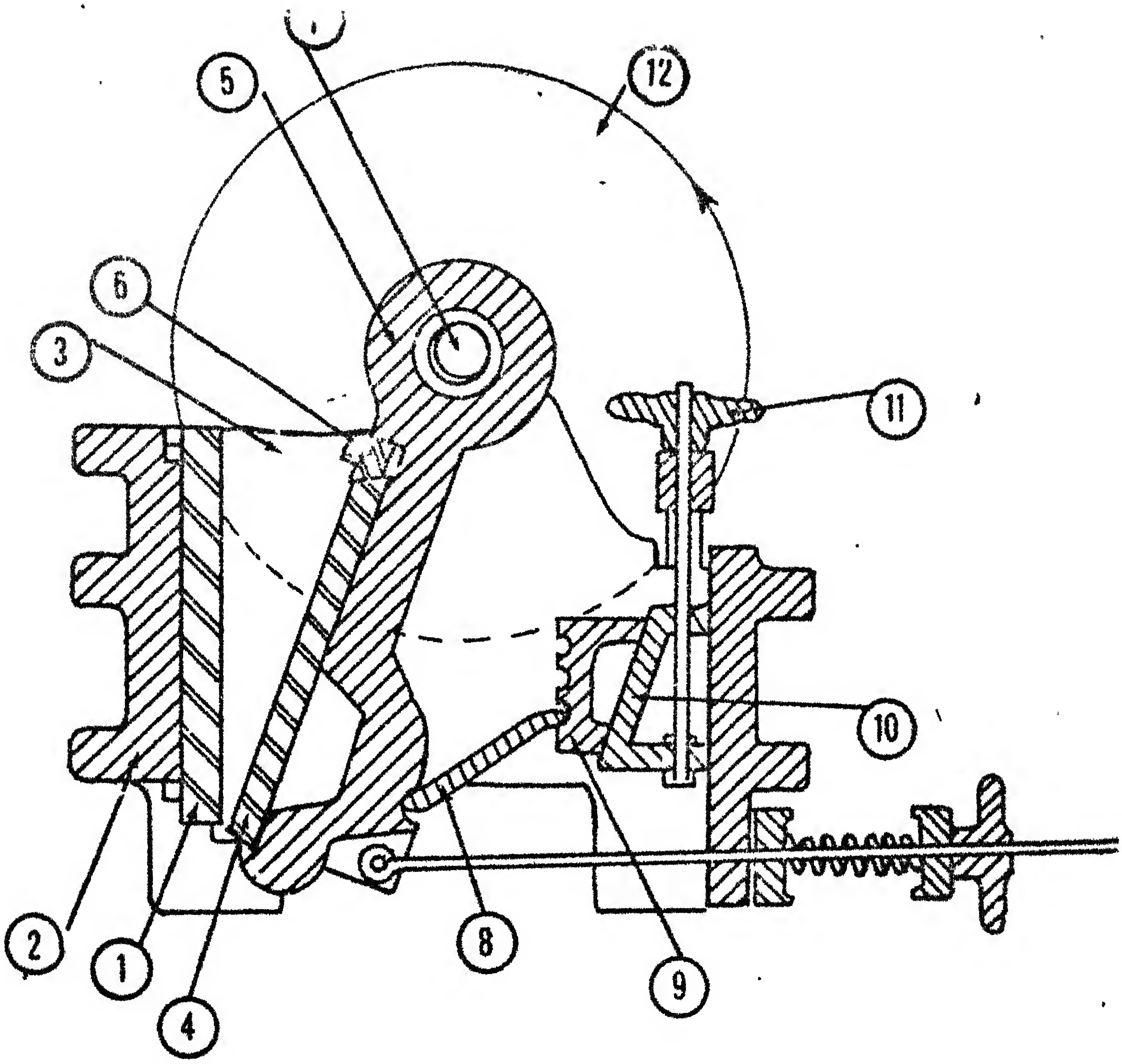


FIG. 2.1 Photograph of Laboratory Size Jaw Crusher for Wear Test.



1	Stationary Jaw Plate	7	Eccentric Shaft
2	Frame	8	Toggle Plate
3	Cheek Plate	9	Toggle Plate Bearing Wedge
4	Movable Jaw Plate	10	Adjusting Wedge
5	Pitman	11	Adjusting Handwheel
6	Pitman Key Wedge	12	Flywheels (Two)

FIG. 2.2 Schematic Diagram of the Main Components of the Jaw Crusher. [32]

movable jaws of the crusher. In all the crushing tests the discharge opening was set at 15 mm ± 2 mm. The discharge opening size was checked with the help of a steel scale from below, while the fly wheel was manually turned through one revolution.

II.1.1 Steel Specification for Jaw Plates

The movable plate was chosen as a reference against which the wear of the stationary plate was compared.

The movable plate of dimensions 280 mm x 178 mm x 30 mm was made from Hadfield manganese steel whose wear was known to be negligible and hence suitable as a reference plate. The hardness of the cast plate was 179 BHN(188 VPN).

The stationary test plates were fabricated from various grades of hot rolled, 12 mm thick steel plates supplied by Tata Iron and Steel Company, Jamshedpur. The steels were produced in Basic Open Hearth furnaces. The specification of the different grades of steels is given in Table 2.1.

The finishing temperature and critical reduction in the last stage of rolling particularly in LA60 steel is very important for proper achievement of mechanical properties. In TISCO upto 16 mm can be successfully controlled rolled using normal heating and rolling pass schedules. Such a

TABLE 2.1 Specification of Different Grades of As Hot Rolled Steels used for Jaw Crusher Test Plates

	Grade	Composition								Hard-ness VPN	ASTM grain size
		C	Mn	Si	S	P	Cr	V	Nb		
1.	IS 226	.19	.78	.250	.025	.028	-	-	-	125	7.5
2.	LA 60	.18	1.59	.282	.027	.026	-	.13	.03	165	7.5-8
3.	TISCRAL	.17	1.28	.357	.053	.034	.70	.08	-	188	8

working process results in a fine grain size structure similar to a normalised structure and thus the latter heat treatment could be dispensed off.

The finished dimensional of the test plate was 200 mm x 180 mm x 12 mm with the corners recessed and the sides facing the movable jaw were chamfered. This permitted proper seating on the ledges in the crushing chamber of the jaw crusher frame and also proper locking by the cheek plates.

II.1.2 Characteristics of Iron Ore

Iron ore was supplied by Tata Iron and Steel Company, Jamshedpur and was mined at Noamundi, Bihar. The ore was sized in a mechanised one processing plant to a range of 10 mm to 40 mm.

Typical analysis of Noamundi iron ore was:

Fe_2O_3 - 94.60 pct.
SiO_2 - 1.61 pct.
Al_2O_3 - 2.53 pct.
Others - 1.26 pct.
Mohr Hardness - 5 to 5.5

Circular punched hole plate screens were used to manually screen the iron ore to obtain a size range

20 mm to 40 mm. This range was maintained throughout the experiment.

II.2 Crushing of Iron Ore

Test plate and reference plate were weighed in a physical balance to the nearest 1 gm. The discharge opening was set at 15 ± 2 mm. One metric tonne of ore was screened through 40 mm and 20 mm screens and crushed in 2 batches of 500 kgm each. The ore was weighed in a salter to the nearest 5 kg before crushing. To ensure that the ore crushed was completely dry it was spread on the floor in a closed room for 2 days before crushing. Between 2 batches the jaws were reset to the original discharge opening of 15 ± 2 mm. Each batch took 3 to 3½ hrs cycle time. The wear ratio minimizes the influence of inevitable parameters from test to test like size distribution, shape and composition of the ore. Each test plate had duplicate runs and the wear ratio values were averaged.

Although it is more rigorous to use volume loss rather than weight loss as a measure of wear, the weight loss is a more practical parameter of wear in this scheme of testing.

Fig.2.3 shows the macrophotograph of a worn out test plate after the crushing test.

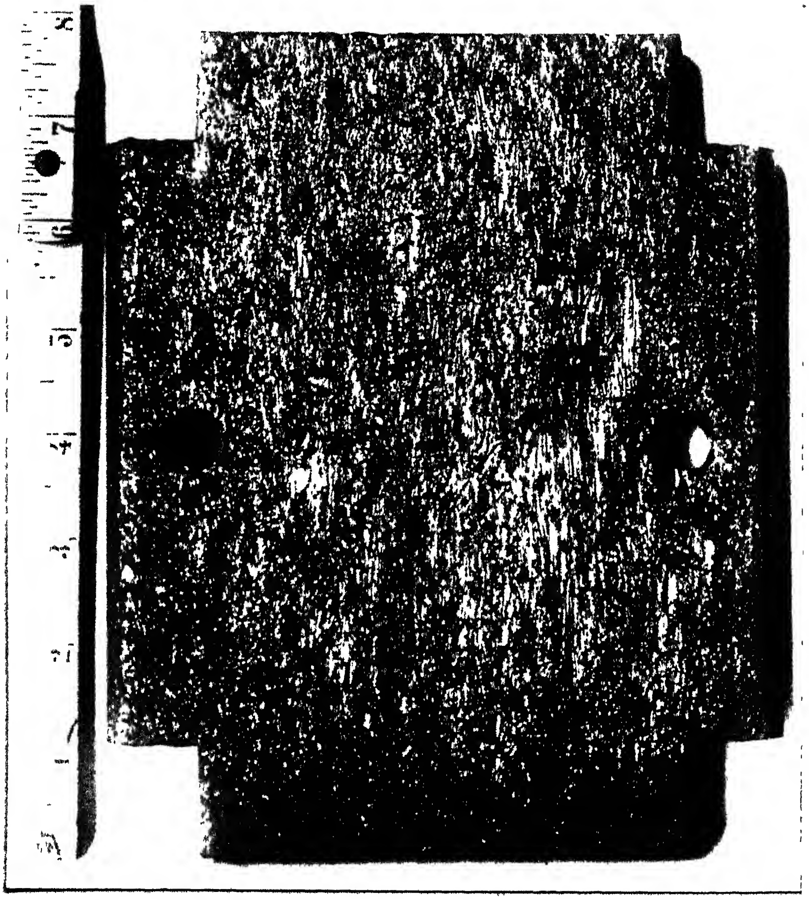


FIG. 2.3 Photograph of IS 226 Grade as Rolled Steel Test Plate after the Crushing Test.

II.3 Heat Treatment Schedule for Various Steel Test Plates

The test plates made from the 3 grades of steel were given various heat treatments as given in Table 2.2.

All the heat treatments were carried out in an electric muffle furnace whose inside chamber dimensions were 1500 mm x 1500 mm x 1500 mm. approx. capable of a Max.temp. of 1150°C The furnace had an automatic temperature controller with an accuracy of ± 5°C.

II.4 Properties of Test Plates

II.4.1 Hardness Measurement of Test Plates

Test plate hardness measurement were carried out on a Wilson make Vickers hardness tester.

The test plates were pickled to remove the scale before hardness measurement. The surface of the plate was also slightly ground and polished to facilitate hardness measurement. This was repeated when hardness was measured after the crushing test. An average of six hardness readings was considered as representative hardness of the plate.

For measuring the transverse hardness in the thickness direction of the test plate after the crushing test, metallographic samples were cut from the centre of test

TABLE 2.2 Heat Treatment Schedule for Test Plates of Various Steel Grades

	Grade of Steel	Austenizing temp. and time	Heat Treatment
1.	IS 226	890°C for ½ hr	a) Normalized b) Water quenched
2.	LA 60	''	a) Normalised b) Water quenched c) Steel plates water quenched and subsequently tempered at 550°C, 600°C, 650°C, resp.
3.	TISCRAL	''	a) Normalised b) Water quenched c) Water quenched followed by tempering at 350°C, 400°C, 450°C, 500°C, 550°C, respectively.

plate of size 12 mm x 12 mm. Transverse hardness readings were taken at distances of 1.6 mm from the worked face of the test plate.

II.4.2 Wear Ratio

The test plate and reference plate after the crushing test were thoroughly cleaned and dried. They were then weighed in a physical balance to the nearest 1 gm.

The wear ratios of the different steels undergone different heat treatments were calculated by the formula

$$\text{Wear ratio (WR)} = \frac{\text{Loss in wt. of test plate}}{\text{Loss in wt. of standard plate}}$$

II.5 Optical Microstructural Examination

Metallographic samples were cut from the corner of test plate after the various heat treatments. The sample size was 12 mm x 12 mm and the longitudinal cut section along the length of test plate was polished. After the crushing test the samples of dimension 12 mm x 12 mm were cut from the centre of the plate in each case, thereby destroying the plate. These samples were polished after mounting in bakelite to preserve the contours of the worked edge. The polishing was done in the usual manner going through the steps of initial grinding on linsher belt, polishing on

various grades of emery papers, and final polishing on wheels using levigated alumina powder of size 2μ. Optical Microscope examination of test plate sample was done on 'Neophot-21' bench type microscope. Photomicrographs of different steel test plate samples undergone various heat treatments were taken. Also photomicrographs of the deformed structure adjacent to the worked edge were taken in the case of each steel at a magnification of 100.

II.6 Scanning Electron Microscopy of the Wear Surface

Samples of size 5 mm x 5 mm were cut from the centre of Tiscral steel test plate after crushing test to study topography of the worn surface. The samples were thoroughly cleaned and dried and preserved in a dessicator before the study. The scanning electron microscopy was done at National Metallurgical Laboratory, Jamshedpur. The model used was 'Stereoscan' of Cambridge Instruments, U.K. The samples were first ultrasonically cleaned in acetone to remove any adherent film and grease sticking to the surface.

The surface was scanned to obtain the typical topography for each sample. The photographs were subsequently taken on a 400 ASA speed 120 roll film at a magnification of 1000.

CHAPTER III

RESULTS

III.1 Hardness of Steels Undergone Various Heat Treatments

III.1.1 Hardness of IS 226 Steel

Figure 3.1 shows the hardness of hot rolled, normalised and water quenched steel test plates. There is no significant difference in the hardness of hot rolled and normalised steel test plates. The maximum hardness was obtained after water quenching treatment.

Figure 3.2 shows the variation of hardness in the transverse direction as a function of distance from the worked surface.

The hardness of work hardened surfaces after the crushing test show a similar trend as the surface hardness achieved after the heat treatments.

III.1.2 Hardness of LA60 Steel

Figure 3.1 shows the hardness of LA 60 steel test plates which underwent various heat treatments. Maximum hardness was obtained in the water quenched steel test plate.

The hardness decreased with increasing tempering temperature, though a hardness peak was obtained at 600°C.

Figure 3.3 shows the variation of hardness in the transverse direction as a function of distance from the worked surface. The hardness of work hardened surfaces after the crushing test reveal a similar trend as the surface hardness achieved after the heat treatments.

III.1.3 Hardness of Tiscral Steel

Figure 3.1 shows the hardness of Tiscral steel test plates which underwent various heat treatments. Maximum hardness was obtained in the water quenched steel test plate. There is a significant drop in hardness of steel test plates on tempering above 400°C.

Tiscral steel test plates show significant increase in surface hardness after the crushing test as compared to that before the test.

III.2 Wear Behaviour of Different Steels

III.2.1 Wear Behaviour of IS 226 Steel

Figure 3.1 shows the wear ratio values of heat treated IS 226 steel test plates. Hot rolled steel test plate has the highest wear ratio and hence the least wear resistance as compared to normalised and water quenched test plates.

Normalising treatment greatly improved the wear resistance. Water quenching treatment deteriorated the wear property as seen by the enhanced wear ratio.

III.2.2 Wear Behaviour of LA 60 Steel

Figure 3.1 shows the wear behaviour of LA 60 steel test plates subjected to various heat treatments. Normalising and water quenching improved the wear resistance of steel as compared to as rolled test plate.

Tempering at 550°C of water quenched steel test plates further improved the wear resistance. Further increase in tempering temperature deteriorated the wear properties as seen by enhanced wear ratios.

III.2.3 Wear Behaviour of Tiscral Steel

Figure 3.1 shows the wear behaviour of Tiscral steel test plates subjected to various heat treatments.

Normalising and water quenching improved the wear resistance as compared to as rolled Tiscral steel test plate.

Tempering of water quenched test plates at 350°C further improves the wear properties. Any further increase in tempering temperature deteriorated the wear properties.

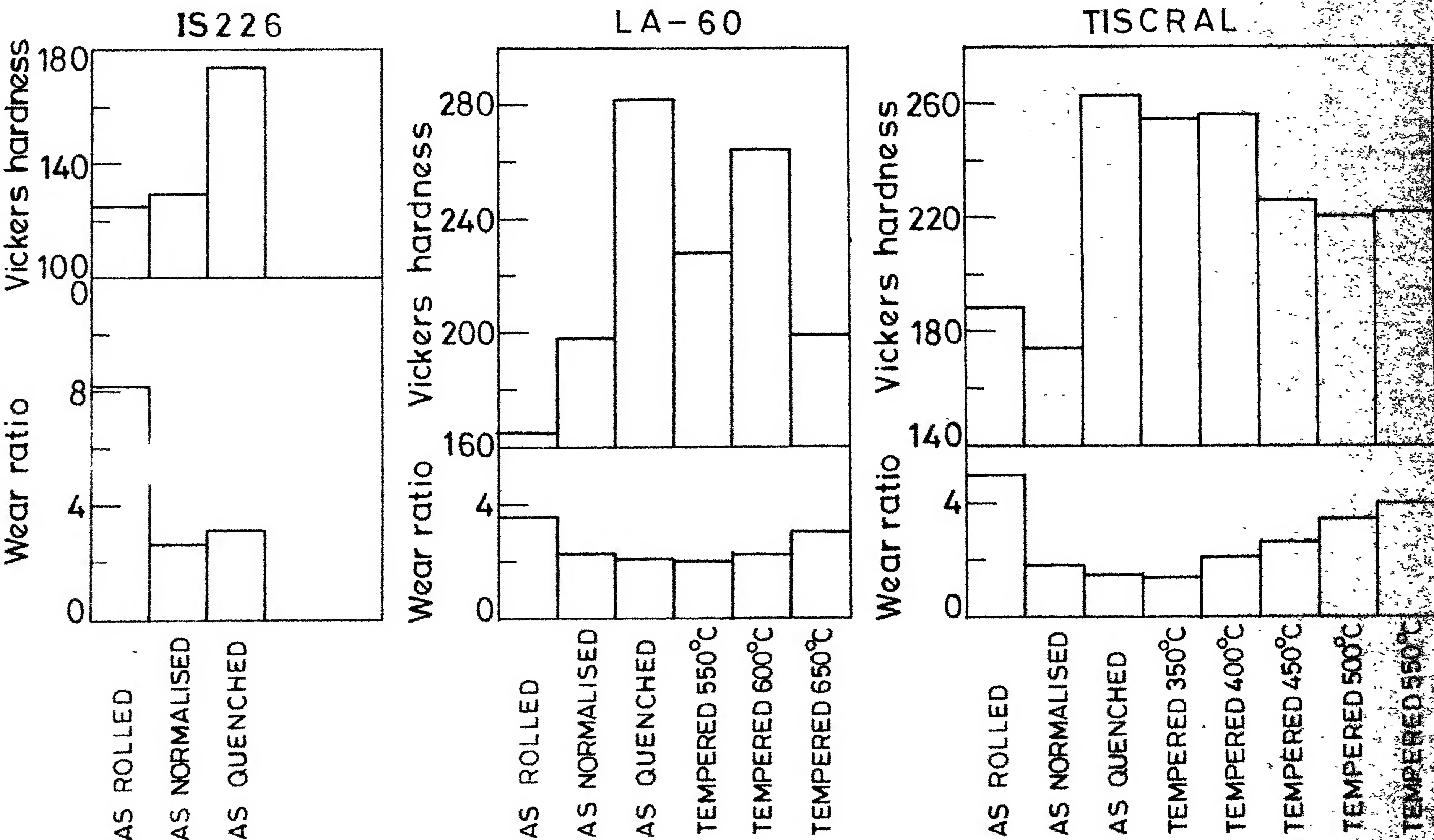


Fig. 3.1 Vickers hardness and wear ratio variations of wrought steels under-gone various heat treatments.

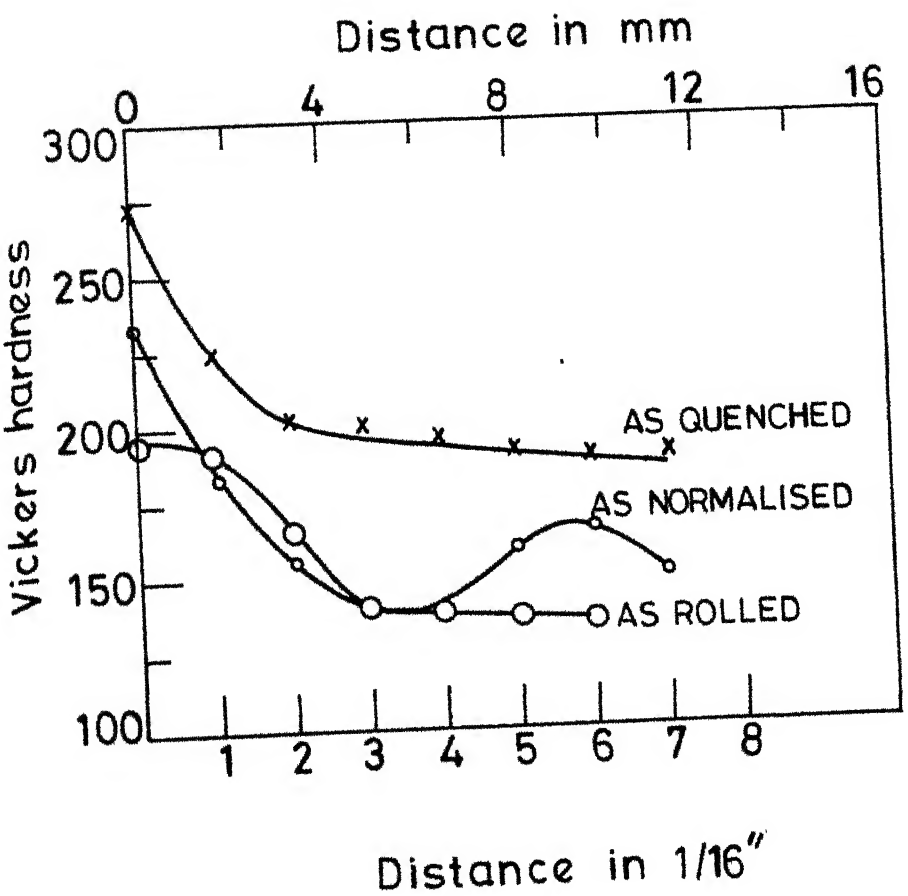


Fig.3.2 Vickers hardness variation of IS226 steel jaw crusher plate in transverse direction after the test.

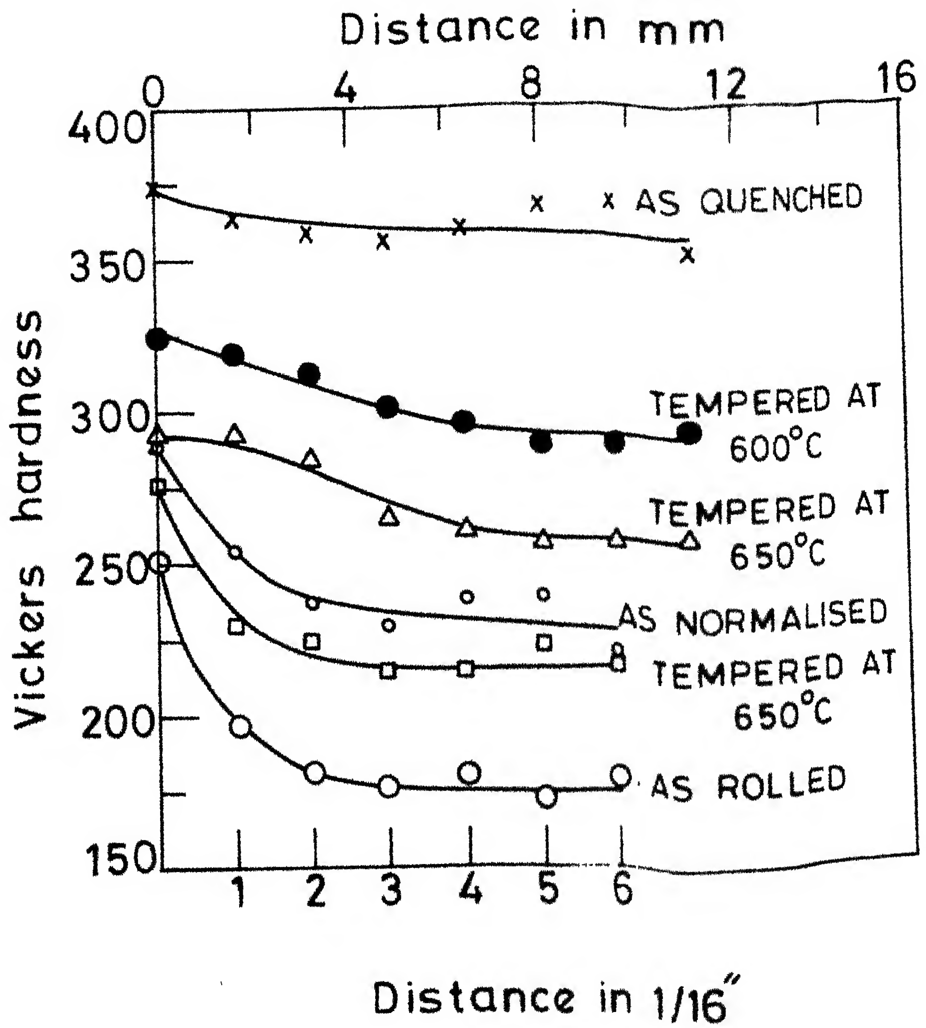


Fig. 3.3 Vickers hardness variation of LA-60 steel jaw crusher plate in transverse direction after the test.

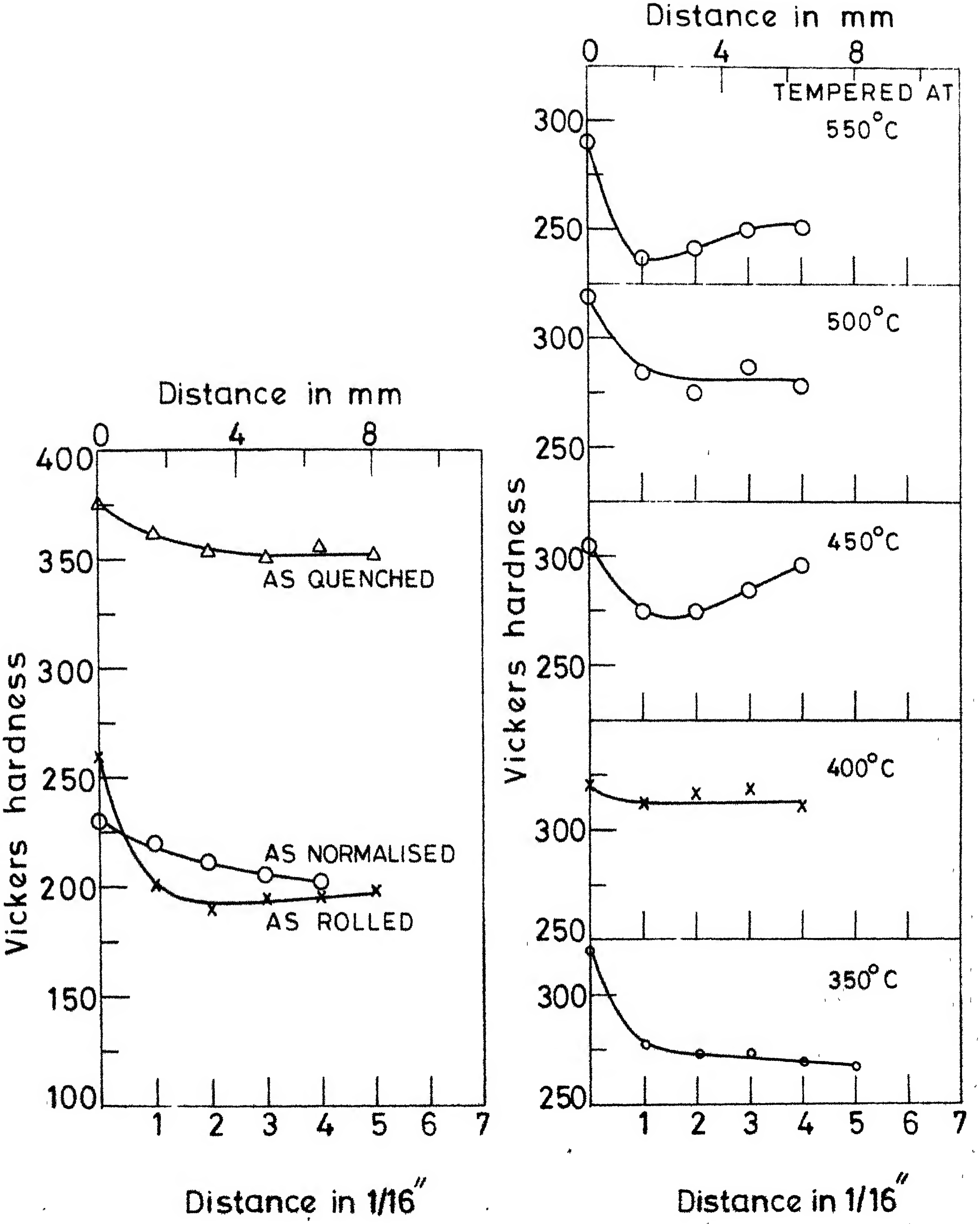


Fig.3.4 Vickers hardness variation of TISCRAL steel jaw crusher plate in transverse direction after the test.

III.3 Microstructural Studies of Different Steels Before and After Crushing Test

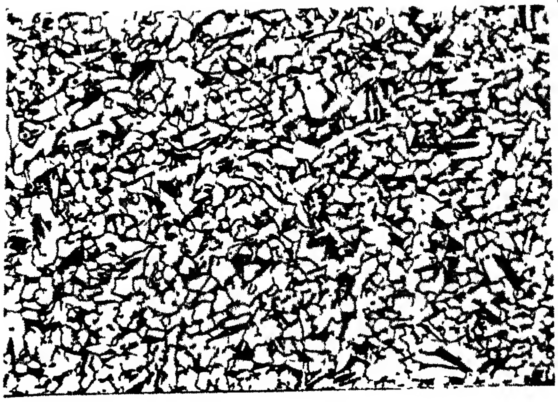
III.3.1 Microstructures of IS 226 Steel Plates

As rolled IS 226 steel has a ferrito-pearlitic structure as shown in Fig. 3.5. The austenitic grain size of the steel is about ASTM 7.5. The pearlite is not resolved at a magnification of 100 and shows slight evidence of banding. The deformed structure of such a plate after the crushing test showed the ferrite more elongated than the pearlite which had deformed to a lesser extent. Normalising treatment resulted in the formation of acicular ferrite with lesser amount of pearlite. The structure was similar to a widmanstatten type microstructure. The deformed structure of such a plate after the crushing test had a more uniformly deformed ferrite and pearlite constituents.

Water quenching treatment resulted in the formation of upper bainite in conjunction with ferrite and isothermally transformed product like pearlite. The deformed structure after the crushing test showed a lesser extent of deformation as compared to normalised and as rolled test plates.

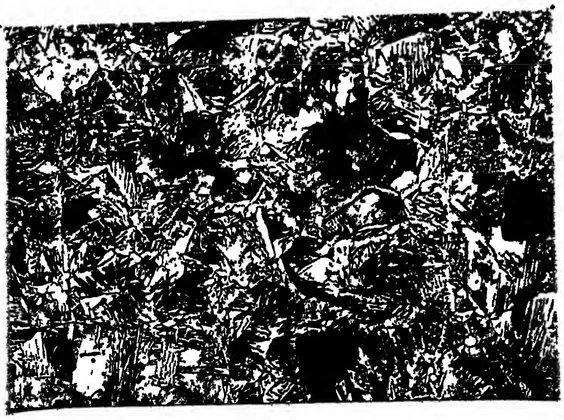
BEFORE CRUSHING

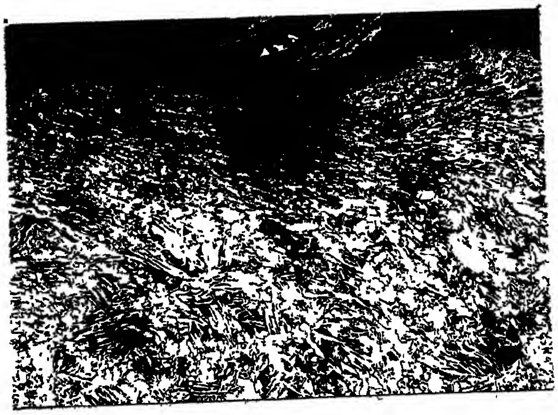
AFTER CRUSHING



As hot rolled.

As normalised





As Water Quenched

FIG. 3.5 Photomicrographs of IS 226 grade Steel before and after the crushing test. X 100.

III.3.2 Microstructures of LA6C Steel Plate

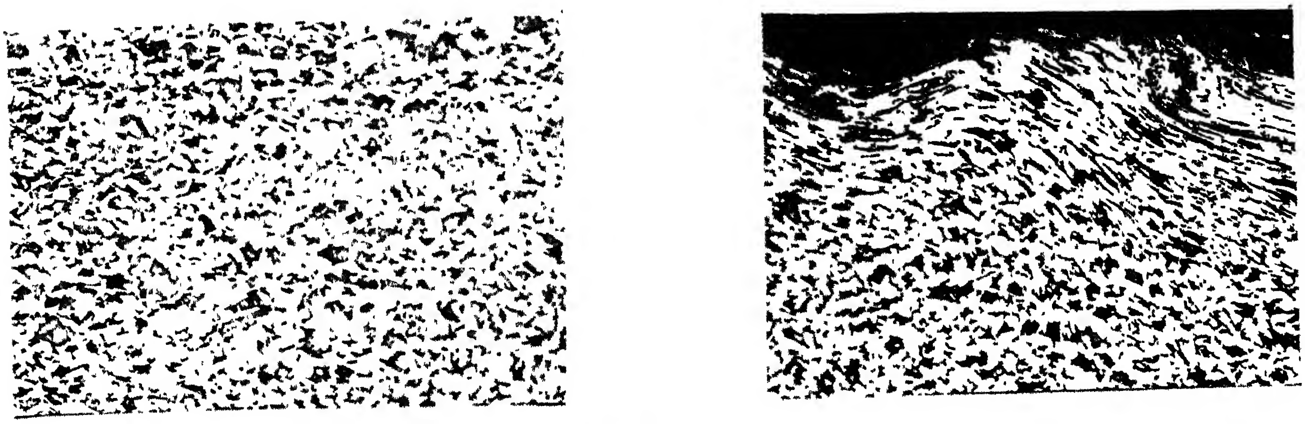
As rolled LA6C steel had a ferrito-pearlitic structure as shown in Fig. 3.6. The austenitic grain size of the steel was between 7.5 to 8 ASTM. The pearlite was not resolved at a magnification of 100. The deformed structure of such a plate shows the flow patterns of the surface deformed during the crushing test.

The normalised steel plate showed a grain refined structure. Deformed structure after the crushing test showed lesser deformed zone as compared to as rolled steel plate.

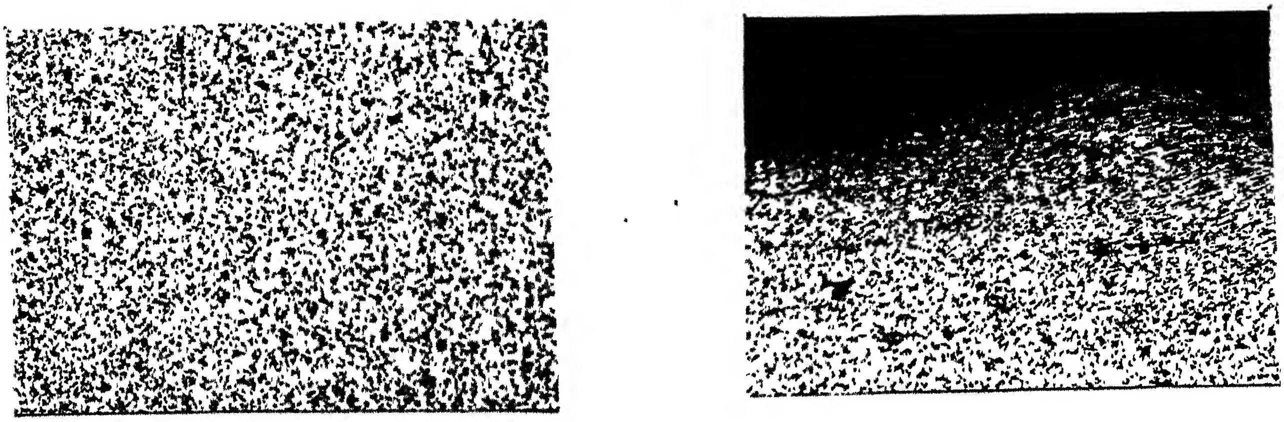
The Water quenching of this grade of steel resulted in a martensitic structure. The deformed structure after the crushing test shows very little material flow as compared to as rolled or normalised steel.

When steel plates of such a grade were tempered at 550°C, 600°C, 650°C respectively after water quenching they resulted in tempered martensitic structures. The deformed structures show the flow patterns after the crushing test. Steel plate tempered at 600°C shows very little deformation. However when tempered at 650°C it resulted in some chip formation on the worn surface caused by the gouging forces during crushing

BEFORE CRUSHING AFTER CRUSHING



As hot rolled



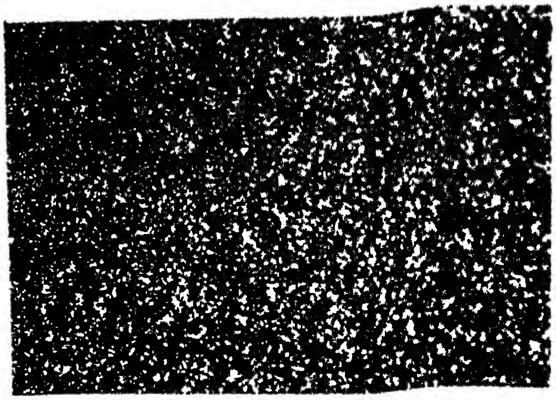
As normalised

As Water Quenched

FIG. 5.6

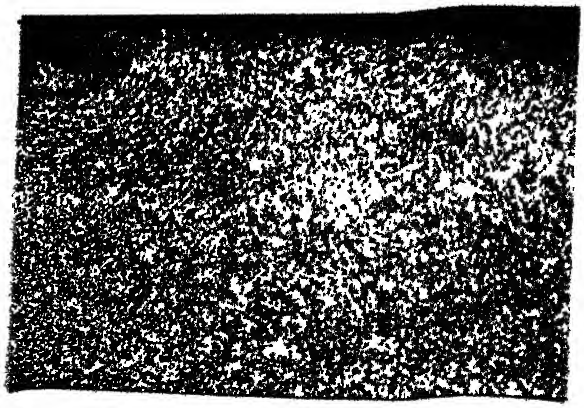
BEFORE CRUSHING

AFTER CRUSHING



Tempered at 550°C

AFTER CRUSHING



Tempered at 600°C

Tempered at 650°C

FIG. 3.6 Photo Micrographs of LA60 grade steel before and after the crushing test.

III.3.3 Microstructure of Tiscral Steel

Figure 3.7 shows the microstructure of as rolled Tiscral steel. The structure is ferrito-pearlitic and the austenitic grain size is about 8 ASTM. Structure also shows some stringers of sulfide inclusions.

The normalised steel plate shows a refined ferrito-pearlitic structure.

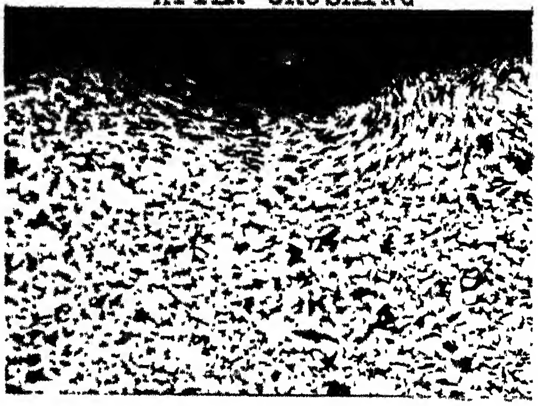
The water quenched structure does not reveal any presence of martensite, indicating that the alloy additions mainly chromium which forms carbides could not go into solution at such an austenizing temperature of 890°C. However this fast rate of cooling does result is a further ferrite/pearlite grain refinement. After tempering between 350°C to 550°C stress relieved structures was evidenced with the absence of other types of carbides.

The extent of deformation as measured from the edge of worn surface from the photomicrographs for these grades of steels is given Table 3.1.

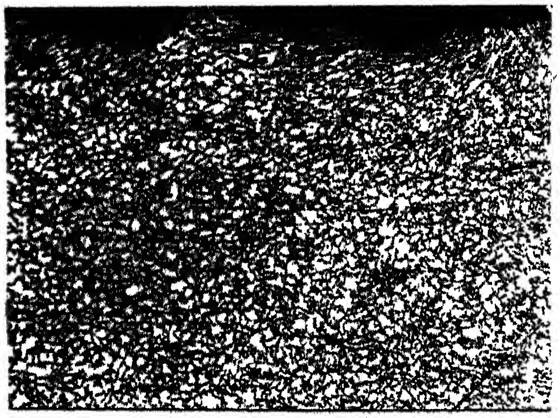
The variation of worked zone thickness in the different heat treated steels has similar trend with respect to the variation noticed after hardness measurement. However the level of thickness in the former is much lower in magnitude as compared to the latter. This may be due

BEFORE CRUSHING

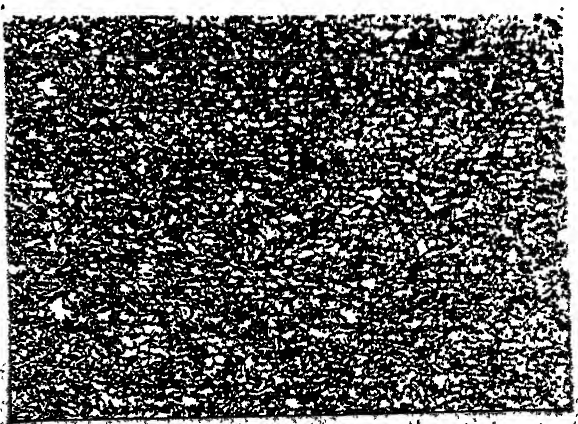
AFTER CRUSHING

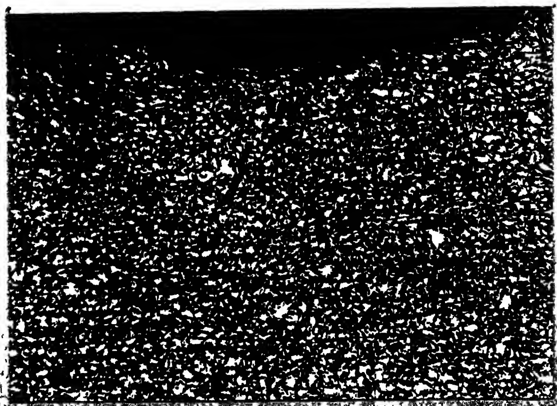


As hot rolled



As normalised



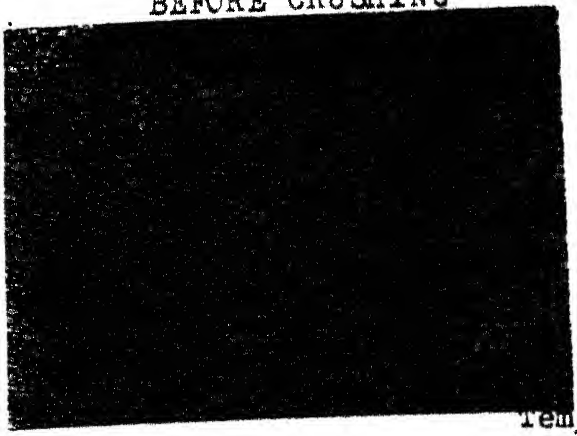


As Water Quenched

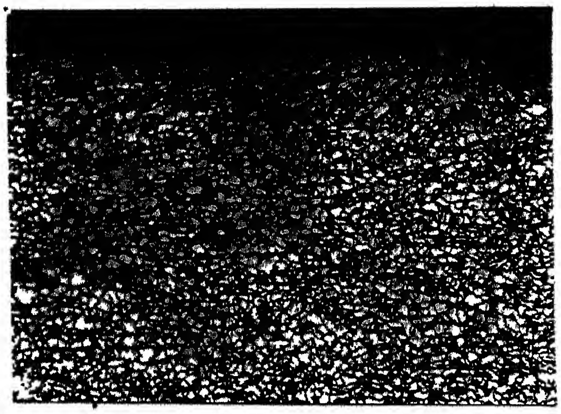
FIG. 5.7 Contd.

BEFORE CRUSHING

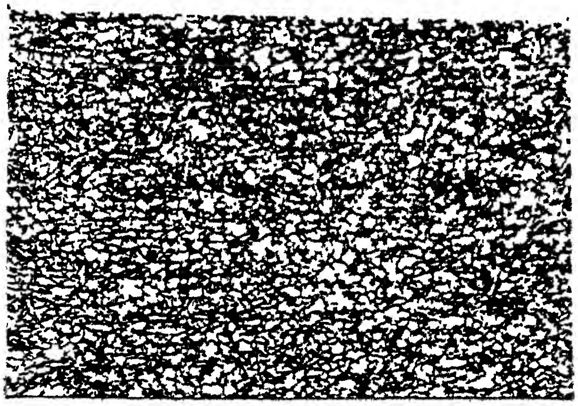
AFTER CRUSHING

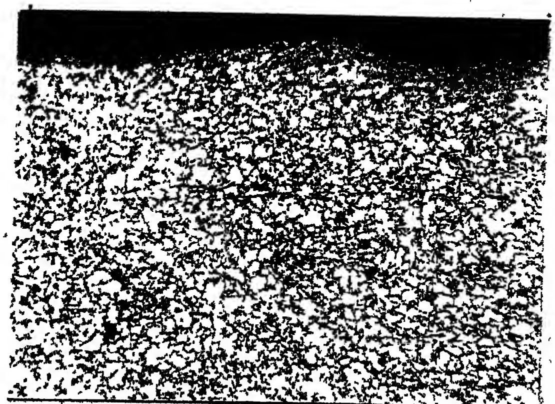


Tempered at 350°C



Tempered at 400°C





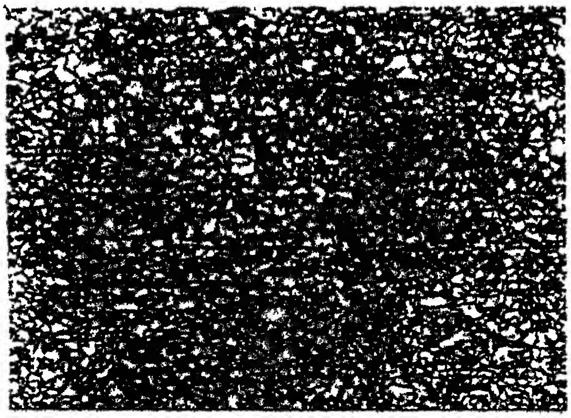
Tempered at 450°C

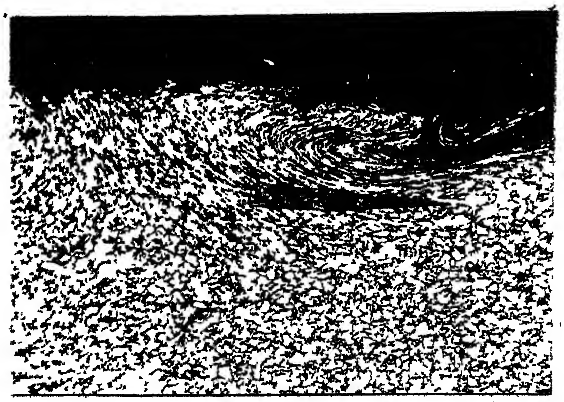
FIG. 3.7

Contd.

BEFORE CRUSHING AFTER CRUSHING

Tempered at $500^{\circ}C$





Tempered at $550^{\circ}C$

FIG. 3.7 Photo Micrographs of Tiscral Grade Steel before and after the crushing test. X 100.

TABLE 3.1 Plastically Deformed Zone as Measured from the Photomicrographs of Steel Plates after Crushing Test

Grade of Steel	Heat Treatment	Width of zone in mm
1. IS 226	As rolled	0.3
	As normalised	0.20
	As water quenched	0.18
2. LA 60	As rolled	0.23
	As normalised	0.20
	As water quenched	0.17
	Temperature at 550°C	0.15
	Tempered at 600°C	0.13
	Tempered at 650°C	0.14
3. Tiscral	As rolled	0.15
	As normalised	0.12
	As water quenched	0.10
	Tempered at 350°C	0.08
	Tempered at 400°C	0.11
	Tempered at 450°C	0.15
	Tempered at 500°C	0.10
	Tempered at 550°C	0.08

to the fact that microstructural examinations were not made at number of places on the test plate and also the fine variations of microstructure might have been missed under optical metallography.

III.4 Scanning Electron Microscopy of Worn Plate Surface

Of the various grades of Steels, Tiscral was selected for scanning electron microscopic study as it showed better wear properties (Fig. 3.1).

The surface topography of the worn plate surfaces after the crushing test as seen using a scanning electron microscope are given in (Fig. 3.8) at a magnification of 1000.

Although all the photomicrographs are not representative ones, some generalised observations have been made. The scanning picture of the as rolled worn steel plate reveals some degree of plastic deformation with depressions randomly distributed, whereas the water quenched steel surface does not exhibit any observable degree of plastic deformation.

When the steel plates were tempered for $\frac{1}{2}$ hr in the temperature range of 350°C to 550°C, the tempered structures were amenable to some degree of plastic defor-

mation but at the same time exhibited toughness. Elevated temperature tempered steel plates show more deformed surface as compared to plates tempered at 350°C and 400°C. This is in consonance with Vickers hardness variation plot given in Fig. 3.1.

CHAPTER IV

DISCUSSION

IV.1 Physical Metallurgy of Steels Investigated

The advantage of carbon in steel has been exploited since the beginning, as it is a cheap alloy addition for getting hardenability. However from fabrication point of view, e.g. welding, this puts forth a disadvantage because of poor weldability. Additions of other alloying elements have been adopted for solid solution strengthening and also hardening through martensitic phase transformation. In this context the role of manganese in plain carbon steels is far wider. As the rate of cooling from homogeneous austenite increases, the temperature at which the transformation to ferrite takes place is reduced and also the transformation rate, increases. Both these factors cause grain refinement of ferrite by favouring nucleation relative to growth. The rate of transformation is dependent on the section of the steel concerned. For example in a low carbon steel containing manganese, on water quenching one may get a little free ferrite and mostly bainite. Increasing carbon refines the bainitic structure. However at the same time even a small amount of bainite is detrimental to the toughness of ferritic steels for it embrittles

the structure due to its greater hardness and acicular structure.

A conventional plain carbon mild has a M_s temperature of the order of 450°C and critical cooling rate greater than 2000°C/sec. In other words a conventional hardening and tempering is not convenient. For strengthening, the manganese content could be raised but at the risk of getting bainite at a faster cooling rate.

It is known that ferrite has a limited solubility of carbon, which during slow cooling precipitates out as cementite on ferrite grain boundaries, and is extremely damaging to toughness[34]. In case the cooling of such steel from austenite range is done fast, one would expect a decreased grain size and lesser amount of diffusion of carbon to form carbides. Both these factors would promote the carbides in much finer distribution, thus helping in toughening the steel. In fact this has been exploited in our present investigation in the case of IS 226 steel which exhibits better wear resistance in as normalised condition.

Pearlite in steel although raises the tensile strength relative to yield strength, reduces impact toughness. In other words for toughening one can not depend on the quantity of pearlite but on other aspects like grain refinement and precipitation hardening with the help of refractory

metal carbides like Vanadium, Niobium carbides, etc. Such a carbide selection is important from two view points: (1) Its low solubility in ferrite, (2) Resistance towards coarsening at elevated temperatures. These concepts have been taken into account in the development of new families of low alloy steels such as LA60 and Tiscral investigated presently. For example, a normalised niobium bearing steel has a finer grain size than the carbon manganese steel and the strengthening is mainly because of a finer grain structure. The precipitation strengthening by niobium carbide could be exploited, if the austenilizing temperature during heat treatment is increased so that NbC could be dissolved in increasing amounts, which will subsequently precipitate out during cooling. An increase in austenizing temperature gives rise to grain coarsening, yet the effect of precipitation hardening predominates, so that overall yield strength is higher. From the view point of toughness one is still at a disadvantage as the grain size in the present case is coarse.

The next alternative in such steels could be thought of by thermomechanical treatment, as close as possible but above the transformation temperature to produce very fine grain size. The dissolved niobium carbide in austenite could

be subsequently precipitated out on the austenite/ferrite interface during cooling. This imparts the best combination of strength and toughness in steel. In conclusion one may say that the important factors in such types of steel would be:

1. Amount of deformation.
2. Finishing temperature of working (in present case, rolling).
3. The rate of cooling.

For the present grades of low alloy steels, the finishing temperature was about 900°C and the steels were normally air cooled. A better proposition to increase yield strength would be to have a still lower finishing temperature associated with a faster cooling rate after rolling. The Tiscral grade steel although not coming in the grade of precipitation hardening steel could be thought of as a candidate for structural parts because of lower production cost relative to LA60 steel.

IV.2 Wear Behaviour of IS 226 Steel

The as rolled IS 226 grade steel plate with a relatively low hardness (125 VPN) as compared to normalised steel, and coarse grain structure is not so tough so as to

offer good wear resistance. This is substantiated by the fact that this grade shows a more deformed ferrite than pearlite (Fig. 3.5) after the crushing test.

Normalising treatment which results in coarse acicular structure, formed perhaps due to rapid cooling resulted in a better wear resistant steel as compared to as rolled steel. Although the hardness of both the plates are comparable yet the normalised plate exhibits higher toughness. This can be inferred from the extent of the deformed zone as seen on the photomicrograph taken after the crushing test (Fig. 3.5).

Water quenching of this grade of steel gives a higher hardness as compared to normalised and as rolled steel. This increase in hardness is due to the formation of a mixed type of structure. Upper bainite with ferrite and pearlite in the microstructure, while increasing the hardness, reduces the impact toughness of the steel plate. The material, thus, could not plastically deform under impact, resulting in portions of the surface being torn away. This is very clearly evident in the photomicrograph of the worn out edge of steel plate after the crushing test (Fig. 3.5).

IV.3 Wear Behaviour of LA60 Steel

The normalising treatment of LA60 steel results in a fine grain structure (Fig. 3.6) thus increasing the hardness as compared to the as rolled steel. Both these factors contribute to increase the wear resistance. The improvement of toughness is reflected in ability to resist plastic flow of the material. The deformed structure of normalised steel plate shows less material flow when compared with as rolled steel plate after the crushing test.

The higher wear resistance of water quenched steel plates over normalised and as rolled steel plates appears to be due to the presence of low carbon martensite in the microstructure. This structure, while increasing the hardness of the plate, appears to have sufficient toughness to give good wear resistance.

Tempering water quenched steel plates at 550°C results in a sharp drop in hardness. Although the hardness is lower compared to water quenched test plate, there is a slight improvement in wear resistance. This can be attributed to the fact that quenched and tempered structure invariably exhibits better toughness than a quenched structure.

Tempering at 600°C shows an increase in hardness. The secondary hardness peak during tempering at this elevated temperature may due to the precipitation of alloy carbides from the matrix. Vanadium carbide in particular has significant solubility in the steel heated to 890°C austenizing temperature and remains in solution after water quenching. This precipitates out in the temperature range 600°C to 700°C, thus increasing the hardness[35]. Niobium in steel has relatively lower solubility at the austenizing temperature mentioned. Solubility data for niobium are available[36].

$$\log_{10} [Nb] [C + \frac{12}{14} N] = - \frac{6770}{T} + 2.26$$

Any increase in temperature for dissolving niobium carbide results in grain coarsening and hence loss of toughness. The steel under the present heat treatment, schedules merely results in grain refinement. Further increase of tempering temperature leads to a softening of the matrix and hence a drop in wear resistance.

IV.4 Wear Behaviour of Tiscral Steel

The as rolled steel of this grade has a hardness on the higher side (188 VPN) as compared with the LA60 steel.

This may be possibly due to the variation in the finishing temperature during hot rolling. Normalising treatment results in a fine grain steel with better wear resistance as compared to as rolled steel plate. This is obvious because grain refinement promotes toughness.

Water quenching treatment results in further grain refinement due to a still drastic cooling effect. This steel lacked martensitic hardenability which may be possibly due to nondissolution of chromium carbides into austenite during austenitizing, thus resulting in a ferrito-pearlitic structure after water quenching. The finer ferrite/pearlite grains as compared to normalised and as rolled plates results in good wear resistance.

Tempering of water quenched steel plates at 350°C results in stress relieving and hence a better wear resistance is obtained as compared to water quenched steel plate. A further increase in tempering temperature results in softening of the matrix and hence a fall in wear resistance. This is confirmed by scanning electron metallography (Fig. 3.8).

It is evident from the above discussion that there exists a relationship between wear resistance and hardness. Higher hardness in general, gives rise to better wear resistance. However this statement should not be taken

rigidly as wear resistance is more a function of toughness of the material than mere hardness.

IS 226 plain carbon steel is much softer than the other two low alloy steels, viz LA60 and Tiscral. This is the reason why the wear ratio of IS 226 steel in as rolled condition is as high as 8 (Fig. 3.1). In the case of LA60 and Tiscral steels, the decrement of the wear ratio with increase in hardness is not as rapid as in the case of IS 226. This appears to be due to a tough matrix with a fine distribution of alloy carbides Fig. 4.1 shows that after a hardness level of 244 VPN, Tiscral steel shows a better wear resistance compared to LA 60, whereas at a lower hardness the position is reverse.

The wear ratio vs surface hardness variation of various heat treated steels after the crushing test (Fig. 4.2) shows a similar trend as in (Fig. 4.1). The band shows two different slopes such that upto a hardness level of 260 VPN the wear ratio drops very rapidly with increase in surface hardness. A further increase in surface hardness does not give rise to such a steep drop of wear ratio. Beyond 320 VPN the wear ratio remains more or less constant. Such a behaviour is demonstrative of the fact that with increased level of work hardening, the variation

in wear resistance becomes less sensitive to surface hardness.

Figure 4.3 shows a plot of the effective width of work hardened zone for different grades of steels after the crushing test. These data were taken from the transverse hardness variation plots (Fig. 3.2 to 3.4). It clearly shows a relationship with the hardness of steels after various heat treatments. However one should be careful while comparing the properties of different water quenched steels. The differences in as quenched structures were obtained as a result of different steel chemistries. Hence it would be useful to correlate microstructure with toughness rather than with hardness which leads one at times to an erroneous conclusion.

CHAPTER V

CONCLUSIONS

1. Although there is a relationship between hardness and wear resistance, toughness as revealed through micro-structural characteristics appears to be the determining factor for wear resistance of steels. There is a positive correlation between microstructure developed after different heat treatments and toughness such that very soft or very hard structures wear far more as compared to a toughened structure.
2. Development of fine grain size in steels through different heat treatments enhances toughness and thereby contributes to the wear resistance of the steels.
3. The work hardening characteristics of steels has an important bearing on wear resistance. Greater the hardness of the work hardened surface greater is the wear resistance.
4. The IS 226 grade of steel being a plain carbon mild steel possesses lower wear resistance as compared to the other two low alloy steels viz, LA60 and Tiscral. However a managable wear resistance could be obtained after its normalising treatment resulting in a fine grain size.

5. Only a marginal improvement of wear resistance is obtained in quenched and tempered LA60 grade of steel. A more finer grain size through thermomechanical treatment is suggested as more attractive for improving wear resistance rather than hardening and tempering treatments.

6. Tiscral grade of steel has the potentialities as wear resistant material, since its wear resistance is superior to LA60 grade. Further more this steel is economical as compared to LA60.

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